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Throughfall and temporal trends of rainfall redistribution in an open tropical rainforest, south-western Amazonia (Rondônia, Brazil)

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Abstract

Throughfall volumes and incident rainfall were measured between 23 August and 2 December 2004 as well as from 6 January to 15 April 2005 for individual rain events of differing intensities and magnitudes in an open tropical rainforest in Rondônia, Brazil. Temporal patterns of throughfall spatial variability were examined. Estimated interception losses were compared to modeled interception losses obtained by applying the revised Gash model in order to identify sources of throughfall variability in open tropical rainforests.

Gross precipitation of 97 events amounted to 1309 mm, 89±5.6% (S.E.) of which reached the forest floor as throughfall. The redistribution of water within the canopy was highly variable in time, which we attribute to the high density of babassu palms *(Orbignya phalerata),* their seasonal leaf growth, and their conducive morphology. We identified a 10-min rainfall intensity threshold of 30 mm h^{-1} above which interception losses were highly variable. This variability is amplified by funneling and shading effects of palms. This interaction between a rainfall variable and vegetation characteristics is relevant for understanding the hydrology of all tropical rainforests with a high palm density.

1. Introduction

Interception loss of rainwater accounts for that amount of rainfall lost due to interception by the canopy and subsequent evaporation either during events as well as after rainfall ceased. The remaining rainfall reaches the forest floor either as throughfall or stemflow. As intercepted water does no longer participate in near-surface hydrological processes (Savenije, 2004), precise knowledge of its magnitude is essential for our understanding and modeling of these processes.

Interception studies were conducted in different climatic regions and forest types, such as temperate broad-leaf (Xiao et al., 2000; Liu et al., 2003) and conifer forests

(Huber and Iroume, 2001; Link et al., 2004), lowland tropical rainforests (Dykes, 1997; Schellekens et al., 1999), and tropical montane forests (Holder, 2004; Munishi and Shear, 2005). Estimates of interception losses in tropical forests are influenced by a high spatial variability of throughfall (Jackson, 1971; Lloyd and Marques, 1988). This variability seems to be caused by canopy features such as leaf or woody frame properties (Herwitz, 1987). Hall (2003) showed that there is a positive correlation between LAI (leaf area index) and interception loss, but that interception loss can vary broadly due to different leaf properties for canopies with the same LAI. Other studies focused on the effect of differing percentage of canopy cover, but found only a weak relationship between throughfall and canopy cover (Tobón Marin et al., 2000; Loescher et al., 2002). Others investigated throughfall amount as a function of distance to tree trunks (Ford and Deans, 1978; Beier et al., 1993; Schroth et al., 1999), but found this distance to be a poor predictor (Keim et al., 2005). Herwitz and Slye (1992) found that neighboring canopy tree crowns can receive different depths of gross rainfall, resulting in a variable pattern of throughfall due to inclined rainfall and shading effects of nearby trees.

Keim et al. (2005) investigated the temporal persistence of spatial patterns of throughfall and found them to be stable for three forest stands with different canopy complexities in the Pacific Northwest, USA.

Our objectives were a) to quantify throughfall in an open tropical rainforest with high palm density, b) to identify any temporal patterns of throughfall spatial variability, and c) to determine the conditions under which this variability complicates the estimation of interception loss.

2. Material and methods

2.1. Site and climate

The study site Rancho Grande is located about 50 km south of Ariquemes (10°18′ S, 62°52′ W, 143 m a.s.l.) in the Brazilian state of Rondônia, which is situated in the south-western part of the Amazon basin.

The area is part of a morphostructural unit known as "Southern Amazon Dissected Highlands" (Planalto Dissecado Sul da Amazônia, Peixoto de Melo et al., 1978), which is characterized by a very pronounced topography with an altitudinal differential of up to 150 m: remnant ridges of Precambrian basement rock, made up of gneisses and granites of the Xingu (Leal et al., 1978) or Jamari Complex (Isotta et al., 1978), are separated by flat valley floors of varying width. Soil orders associated with this morphostructural unit are Ultisols, Oxisols, and Inceptisols and Entisols (Soil Survey Staff, 1999) on steep slopes and along streams, respectively.

The vegetation at this terra firme study site consists of primary open tropical rainforest (Floresta Ombrófila Aberta) with a large number of palm trees. In Rondônia open tropical rainforest amounts to 55% of the total vegetation area (Pequeno et al., 2002). It is characterized by a discontinuous upper canopy of up to 35 m height with emergent trees up to 45 m tall, permitting the sun light to reach the understory and thereby facilitating a dense undergrowth. Roberts et. al (1996) determined a LAI of 4.6 for an open tropical rainforest at the ecological reserve "Reserva Jaru" about 100 km east of Rancho Grande, compared to a LAI of 6.1 for a dense tropical rainforest measured 60 km north from Manaus. For trees with DBH (diameter at breast height) >5 cm, the tree density is 813 ha^{-1} including 108 palms, and 520 ha^{-1} for DBH>10 cm, including 81 palms. Among the 94 species with DBH>5 cm (89 species with DBH>10 cm) the most abundant are Pama verdadeira (*Brosimum gaudichaudii, Moraceae*) and Breu rosa (*Protium sp., Burseraceae*). The most common palm species in this region are Paxiuba bariguda (*Iriartea deltoidea*), followed by the babassu palm (*Orbignya phalerata*, local name: babaçu) with a density of 36 full-grown and 115 young individuals per hectare.

The climate of Rondônia is tropical wet and dry (Köppen's Aw). The mean annual temperature is about 27°C. Variations in mean monthly temperature maxima and minima are on average 12.4°C, ranging from 10.6°C in March to 15.7°C in August. Mean annual precipitation is 2300 mm with a marked dry period from July through September. On average, 144 days with rainfall are registered per year, 133 of which fall into the rainy season. On average, 20 rain days occur during the peak of the rainy season, from December through March. The seasonal variation in average daily relative humidity levels ranges from 65% in July to 80% in December (averages of the years 1984–2003, Schmitz, personal communication).

2.2. Experimental design and data analysis

Throughfall and gross rainfall were measured on event basis between 23 August and 2 December 2004 as well as from 6 January to 15 April 2005, whilst stemflow was measured from 27 January up to 20 March 2005.

2.2.1. Gross rainfall

A tipping bucket rain gauge (Hydrological Services P/L, Liverpool Australia) with a resolution of 0.254 mm and a Campbell logger recorded 5-min rainfall intensity values on a pasture about 400 m from the forest. In addition, incident rainfall was measured with three trough-type collectors. One was read manually and the other two were connected to one single tipping bucket logged by a Hobo Event Logger (Onset) with a resolution of 0.51 mm. The collectors, installed on support 1 m above ground, were made out of 150 mm diameter PVC pipes, which were connected via flexible tubes to 20 L plastic canisters. The total collecting area per collector was 980 cm^2. To avoid splash losses a orifice with a width (70 mm) smaller than the diameter was cut out of the PVC pipes. The rainfall quantity data of the trough-type collectors was only used to calibrate the trough collector volumes with volumes measured by the automatic weather station (calibration factor: 1.1, R^2=0.99).

In order to qualify for an event, at least 0.5 mm of rainfall must have been recorded in half an hour. Events are separated by at least two hours without rain.

2.2.2. Throughfall

Throughfall quantities per event were measured manually with 20 collectors as described above, which were leveled and cleaned of litter after each event. The measured throughfall was corrected by the calibration factor described previously.

The collectors were distributed throughout a heavily instrumented catchment with a maximum distance of 170 m between collectors. Their sites were chosen at random, but with a view towards minimizing disturbance instead of a strictly random distribution with random relocation of collectors (Lloyd and Marques, 1988); Helvey and Patric (1965) recommended such a random relocation, but only for interception studies on a weekly or monthly basis but not on an event basis as in our case. Even so, we attempted to cover the small-scale variability in vegetation.

Two hours after every event or alternatively the next morning for events which ended after 09:00 PM, we emptied the collectors and quantified the throughfall with graduated cylinders of three different sizes. For events with less or equal to 5mm, between 5 and 15 mm and events bigger or equal to 15 mm graduated cylinders of 100 ml, 500 ml and 1000 ml were used, respectively.

Because throughfall was not normally distributed for 24% of the events, the median of all collectors was used to estimate throughfall per event.

To determine whether high or low throughfall areas persist between events Keim et al. (2005) used the standardized throughfall, $\tilde{T}F$, for each sample point i:

$$\tilde{T}F_i = \frac{TF_i - \bar{T}F}{s_{TF}}, \tag{1}$$

where TF_i is the throughfall at sampling point i, $\bar{T}F$ is the mean throughfall for a given event, and s_{TF} its standard deviation. We used the same equation, but with the median and its standard deviation (Hoaglin et al., 2000) instead of the mean and its standard deviation.

2.2.3. Stemflow

Stemflow was measured for 24 trees in three different DBH classes and for 8 large aborescent babassu palms. The volume in mm per event was calculated by the method applied by Hanchi and Rapp (1997) for each DBH class. The instrumentation and measurement procedure of stemflow is described in detail in a parallel work Werther (2005)[1]. For our study, we used an average value for stemflow of 8.0% of incident rainfall.

2.3. The revised Gash model

2.3.1. Model description

The original and the revised Gash model (Gash, 1979; Gash et al., 1995) assume that the two major factors which control the evaporation of intercepted rainfall are 1) the duration of evaporation from the saturated canopy per event plus the associated evaporation rate and 2) the canopy saturation capacity as well as the number of times the saturated canopy is dried out completely after an event.

In comparison to other interception models, the Gash model is characterized by its low data demand. In cases of low data availability a simple regression equation is often used to describe interception:

$$I = aP_G + b\,, \tag{2}$$

where I is the interception in mm of incident rain, P_G is the gross rainfall and a and b are the regression coefficients. Unlike the regression equation, the Gash model is

[1]Werther, L.: Stemflow in an open tropical rainforest in Rondônia, Brazil, M.Sc. Thesis, University of Potsdam, Potsdam, unpublished, 2005.

based on a simple but realistic approach to describe the interception process. The revised Gash model is an adaptation of the original model to account for stands with sparse canopies.

The amount of rainfall needed to completely saturate the canopy, P_G', is expressed as

$$P'_G = \frac{-\overline{R} S_c}{\overline{E}_c} \ln \left[1 - \frac{\overline{E}_c}{\overline{R}} \right], \tag{3}$$

where $\overline{R}$ is the mean rainfall rate and $\overline{E}_c$ is the mean evaporation rate from the canopy. The canopy capacity per unit area of cover, $S_c = S/c$, is the amount of water remaining on the saturated canopy after rainfall and throughfall ceased.

To get an estimate for the mean rainfall rate falling onto the saturated canopy, $\overline{R}$ is calculated for all hours exceeding a certain threshold of hourly rainfall. We adopted a value of 0.5 mm h^{-1} in accordance to Gash (1979), Lloyd et al. (1988) and Schellekens et al. (1999).

Interception is calculated in several steps by dividing the rainfall events into three phases. The first considers the stage before the canopy is saturated, with $P_G < P'_G$, the second covers the part of the rainfall event when the canopy is saturated, and the last stage refers to the evaporation after the rain ceased. This trichotomy leads towards the six equations summarized in Table 1. Total interception is calculated as the sum of these different components. According to Gash (1979) and Lloyd et al. (1988), we calculated mean rainfall intensity for all hours with P_G greater 0.5 mm h^{-1}; however, the difference to all hours of rainfall is not great due to the short and intense rainfall events typical for this climate.

Due to high variability of throughfall measurements $\overline{E}_c$ could not be determined by regressing interception loss on gross rainfall, which yields $\overline{E}_c/\overline{R}$ (Gash, 1979). Instead we adopted the value of 0.21 mm h^{-1} found by Lloyd (1988) for central Amazonia, which appears to be typical for tropical forests (Hall, 2003).

2.3.2. Forest parameters

Canopy interception parameters are usually estimated by gross rainfall and throughfall data collected on an event or weekly basis (Leyton et al., 1967; Gash and Morton, 1978; Rowe, 1983; Jetten, 1996), compensating short-term variability. The canopy capacity is often determined by the method of Leyton et al. (1967), where in a plot of throughfall versus rainfall a line with a slope of one is drawn passing through events with maximum throughfall. The intercept with the gross rainfall axis is interpreted as the value for canopy storage.

This method however, is not suitable for forests with a high spatial variability of throughfall. Instead, we employed a slightly modified version of the method of Lloyd et al. (1988). For each collector, we regressed throughfall on gross precipitation for events with $1.5 \leq P_G \leq 15.0$ mm. Because of outliers and high-leverage points, we used a robust regression method based on Tukey's beweight (Hoaglin et al., 2000). To ensure the drying out of the canopy, only events separated by dry periods of at least 6 h were considered in these calculations. It is assumed that for the small events used for this approach evaporation can be ignored. Stemflow, however, can't be neglected for this kind of forest (Werther, 2005)[1]. In contrast to Lloyd et al. (Lloyd et al., 1988), we defined for each collector a regression of throughfall over the difference of gross rainfall and the stemflow proportion

$$TF = a(P_G - p_t * P_G) + b \tag{4}$$

with a as the slope of the regression and b the intercept. The canopy capacity, S_c, is determined as the mean intercept of the regression lines with the x-axis. The standard deviation of S_c was calculated using the mean standard deviation of b for all collectors.

We estimated the free throughfall coefficient, p, with digital photographs. At each of three equidistant points in the catchment, we laid out two 10-m long transects normal to each other, along which we took black-and-white pictures of the canopy, with a camera mounted on a level, in one meter intervals, resulting in a total of 60 pictures. An image editing program was used to find the center of the images to verify if the center was

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covered by the canopy or not, which yielded a proportion of canopy coverage, c, and hence the free throughfall coefficient $p=1-c$.

P'_G, the rainfall amount needed to completely saturate the canopy, was then calculated according to

$$P'_G = S_C(1+p)\,. \tag{5}$$

3. Results and discussion

3.1. Gross rainfall

The total incident rainfall at Rancho Grande from August 2004 to July 2005 was 2352 mm, being in line with the mean annual rainfall amount of the previous 20 years of 2300 mm. The month of August, however, was far too wet (Fig. 2), due to an early start of the rainy season. In addition, April and June were much drier than the respective 20-year average.

We collected 97 events over the two monitoring periods, with a total of gross precipitation of 1309 mm. Rainfall intensity for all measured events and all hours with intensities >0.5 mm h^{-1} averaged 6.66 mm h^{-1}. Maximum 10-min and 60-min intensities were 100.61 mm h^{-1} and 57.91 mm h^{-1}, respectively. Durations shorter than 1 h were found for 44% of the events.

3.2. Throughfall

All throughfall results are summarized in Table 2. The total measured throughfall volume of the whole study period was 1175 mm or 89.8±5.6% (S.E.) of incident rainfall. This percentage is in line with results of other studies. Ubarana (1996) reported 87% of observed total throughfall for Reserva Jaru site within about 100 km of our site. These values fall within the range of throughfall values reported for rainforests in the Amazon basin with 78–91% (Lloyd and Marques, 1988; Elsenbeer et al., 1994; Filoso et al., 1999; Tobón Marin et al., 2000), in Asia of about 80% (Sinun et al., 1992; Dykes, 1997) or Africa with 92–97% (Chuyong et al., 2004).

For 18 events throughfall volumes of more than 100% of P_G were measured and throughfall plus the proportional stemflow volumes of the incident rainfall exceeded rainfall volumes in 25 cases, resulting in negative values for interception loss. Despite two cases in August negative values did occur more frequently from November onwards. Since negative values for average interception loss per event can only be expected for some special forest types, e.g. mountain cloud forests (Holder, 2004), there is either an underestimation of rainfall or an overestimation of throughfall quantities for these events. Our own manual rainfall measurements next to the automatic rain gauge, however, preclude the former possibility. Therefore, these negative values are likely to result from an effect induced by not only the spatial variability of throughfall, but also the temporal variability of throughfall in individual collectors as discussed hereafter.

Throughfall amounts vary highly among collectors due to drip points and caps above the collectors (Loescher et al., 2002). The plot of normalized throughfall, $\tilde{T}F$ (Fig. 2) is ranked by mean $\tilde{T}F$ per collector. Since each dot represents one throughfall observation at a single collector, the plot shows the temporal variability of throughfall for each collector. Although several collectors registered frequently more (e.g. collectors 14 or 20) or less (e.g. collectors 2 or 13) than the median throughfall per event, as indicated by the deviation from the horizontal axis; none of the collectors deviated persistently in either direction. The temporal variability in some of our collectors was up to three times as high as in others (e.g. collectors 7 and 19). In contrast to our results, Keim et al. (2005) found a much lower temporal variability for coniferous and deciduous stands in the Pacific Northwest, USA, which we attribute to the differences in homogeneity of the two forest types.

Figure 2 does not show whether the variability of single collectors is temporally stable. By plotting throughfall as a percentage of P_G over time per collector, a temporal trend in some of the collectors becomes evident. Figure 3 shows two impressive examples of this temporal variability of throughfall proportions. In both cases, throughfall rises sharply from early October towards December. During the second study period, the opposite trend can be observed of the two collectors. For both periods, collector no. 2 (Fig. 3a) shows a pattern only for large, high intensive events, while collector no. 19 (Fig. 3b) shows a pattern regardless of event size or intensity. The photographs in Fig. 3 were taken upright from the middle of the collectors, showing the canopy structures at the respective site. Eleven out of twenty collectors showed temporal trends in throughfall proportions. Among the nine remaining collectors without any temporal trends, five collectors do not have palm leaves above them. Only one collector without palm tree parts above it shows a slight temporal effect in the beginning of the first study period. Nevertheless, the results show that strong temporal patterns of throughfall volumes were observed beneath palms. Individual palm leaves can act as a natural gutter thanks to the typical, convex form of the petioles, which enables them to collect more water than some trees of the understory. The water is either diverted to the stems or is funneled towards drip points. As babassu palm leaves grow, they do not just increase in size, but move vertically and horizontally within the canopy due to their own weight gain. If the palm leaves move, the associated drip points move as well and collectors at fixed positions may record a temporal pattern of throughfall percentages. As the growing season of babassu palms falls within the rainy season (Anderson, 1983), these temporal patterns start in October and become more obvious with the beginning of November.

These observations suggest a significant redistribution of water within the canopy and a temporal pattern of this redistribution. Because this redistribution is linked to babassu palms, our findings are pertinent to the understanding of the hydrology of palm-dominated tropical rainforests. Such forests are wide-spread from the eastern to southwestern region of the Amazon basin (Kahn and Granville, 1992). In some regions, this invasive plant forms pure populations in regenerating forest gaps or in abandoned pastures (Lorenzi, 2002). Regional forest surveys do not include subterranean-stemmed palms, whose leaves may reach a length 9 m. Several authors (Jordan, 1978; Lloyd and Marques, 1988; Manfroi et al., 2004) found that small trees growing

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in the understory of forests often produce more stemflow than emergent trees with a greater DBH. Consequently, the juvenile palm leaves may be at least as important as leaves from adult palms concerning the redistribution and uneven input of rainfall to the forest floor. Other researchers reported high palm densities in the understory of dense rainforests, with individuals reaching heights of 2–4 m in Colombian Amazonia (Tobón Marin et al., 2000) or 4–5 m in Central Brazilian Amazonia (Lloyd and Marques, 1988). More research with an appropriate sampling design is required to evaluate the importance of small palms in redistributing water and producing locally high inputs of throughfall to the forest floor.

3.3. The revised Gash model

Table 3 summarizes the meteorological and canopy input parameters for the interception modeling. Beside canopy cover, the most sensitive parameter in the original and revised Gash model is the canopy storage, S_c. The value of 0.72±0.44 mm (S.E.) for S_c for our site does not differs from the 1.03 mm reported for the Reserva Jaru, Rondônia (Ubarana, 1996) or from the 1.15 mm found by Schellekens et al. (1999) for a lowland tropical rainforest in Puerto Rico. But it is lower than the 1.25 mm and 1.16–1.55 mm reported for other sites in Amazonia (Ubarana, 1996; Tobón Marin et al., 2000, respectively).

Free throughfall values for tropical rainforests obtained by photographic techniques ranging from 0.03 to 0.08 (Lloyd et al., 1988; Ubarana, 1996), differ clearly from values determined by more subjective methods based on the method of Leyton et al. (1967), which range from 0.23 to 0.32 (Jackson, 1975; Elsenbeer et al., 1994; Schellekens et al., 1999). According to the definition of free throughfall as the amount of water falling through the canopy without striking it, the photographic techniques seem to estimate this proportion better than the other methods that are influenced by that part of throughfall striking the canopy but reaching the forest floor before the canopy is saturated.

Figure 4 shows the modeled cumulative interception losses and those calculated from median throughfall (further referred as “calculated interception”) for all events. As discussed in the previous section, negative interception losses were observed due to the occasional overestimation of average throughfall. It is clear from Fig. 4a that the curve of modeled interception losses fits the calculated values quite well up to the beginning of November, when the number of events with negative interception losses increased and the growing season of the babassu palm started. If the assumption is true that the redistribution of rainfall water within the canopy due to the babassu palms is responsible for the difference of the curves of modeled and calculated values, then these differences should not be observed for throughfall medians from collectors with no obvious palm influence or for all collectors which do not show any temporal trends. Figures 4b and 4c show a better agreement between calculated and modeled values, due to higher calculated interception loss from mid-November on. The better fit for collectors without temporal patterns (Fig. 4b) is plausible because the excluded collectors tend towards higher throughfall which is most obvious for collectors 7, 17 and 19 (Fig. 2). In addition, the increase of calculated cumulative interception losses is greater if fewer collectors with palm influence (14, 4, 0 in Figs. 4a, 4b and 4c, respectively) are used for the calculations. But the crucial point is that the curves in Figs. 4b and 4c still show the same trends of calculated interception loss. Hence, this pattern is unlikely to be induced, but rather amplified, by the presence or absence of drip points associated with palms.

In order to identify causes for the trends in calculated interception loss, we examined the dependency of interception loss on rainfall intensity. The relationship of calculated interception loss and maximum 10-min rainfall intensities (Fig. 5) reveals a rainfall intensity threshold of about 30 mm h^{-1}, beyond which interception values show considerable scatter. When cumulative calculated and modeled interception losses are plotted separately for events with rainfall intensities below and above this threshold (Figs. 6a and 6b, respectively), the calculated cumulative curve for low intensities shows a uniform trend and coincide with the lower limit of uncertainty of the expected values. In contrast, the calculated interception losses for high intensity events show a variable trend and exceed the uncertainty limits of the modeled values. As the calculated interception loss is inferred from the throughfall median, we conclude that for high intensity events it is not adequate to estimate the average throughfall from randomly distributed collectors. Instead, the spatial pattern of drip points and hence of throughfall must be known to estimate a weighted throughfall mean. Such a weighted throughfall mean might improve the estimation of interception losses also at low rainfall intensities.

It should be kept in mind that any discrepancy between modeled and actual interception losses derives from the uncertainty not only of S_C, but also of mean evaporation. Schellekens et al. (1999), using the original Gash model, reported good predictability of cumulated throughfall for a maritime dense tropical rainforest in Puerto Rico as long as the value of $E_w/\overline{R}$ was derived from the regression of interception and event rainfall. Although some of their events exceeded our 10-min rainfall intensity threshold (Schellekens, private communication), the authors did not report high negative interception values for single events. Lloyd et al. (1988) stated that the original Gash model performed adequately for a dense tropical rainforest in Central Amazonia, although they did get negative values for interception loss, which they attributed to the low number of collectors and high spatial variability. It would be interesting to know if the negative interception values found by Lloyd et al. (1988) were associated to maximum 10-min intensities greater than 30 mm h^{1}.

4. Conclusions

Tropical rain forest are the most difficult forest type in which to measure throughfall, stemflow and consequently to determine interception loss. We calculated a total measured throughfall volume of 89.8±5.6% of incident rainfall.

The results of our experiment suggest furthermore that in open tropical rainforests with high palm densities, the palms play an important role in generating dynamic spatial variability of throughfall. At our study site, the babassu palm *(Orbignya phalerata)* is the most important species responsible for high redistribution of rainfall within the canopy due to their conducive morphology and their high stem density. The spatial pattern of

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water input to the forest floor shows temporal patterns, which appear to be controlled by babassu palms and their leaf growth. Furthermore, the relationship of 10-min rainfall intensity and interception loss revealed a threshold of 30 mm h^{-1} above which the calculated interception losses are highly variable. A comparison of calculated and modeled interception losses showed that this variability can be greatly amplified by funneling and shading effects of palms (Fig. 4). We conclude that for high intensity events it is not possible to estimate interception loss from median throughfall. If the spatial pattern of throughfall is known, a weighted mean throughfall might yield better results.

As the babassu palm is common throughout the Amazon basin (Kahn and Granville, 1992) in upland as well as in seasonal swamp forests, the role of pronounced redistribution of rainfall within the canopy due to these palms should be considered in future research. As the high intensity events responsible for the large variability in throughfall tend to be of high magnitude as well, our results are relevant for the hydrology not only of open tropical rainforest dominated by palms, but perhaps as well for dense tropical rainforest with a high density of juvenile palms in the understory.

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Table 1. The components of the revised interception loss model according to Gash (1995).

Component of interception loss	Formulation of components
For m small storms, insufficient to saturate the canopy	$c\sum_{j=1}^{m} P_{G,j}$
Wetting up the canopy, for n storms $>P'_G$ which saturate the canopy	$ncP'_G - ncS_c$
Evaporation from saturation until rainfall ceases	$\frac{c\overline{E_c}}{\overline{R}}\sum_{j=1}^{n}(P_{G,j} - P'_G)$
Evaporation after rainfall ceases	ncS_c
Evaporation from trunks, for q storms $>S_t/p_t$, which saturate the trunks and for $n-q$ storms, which do not	$qS_c + p_t\sum_{j=1}^{n-q} P_{G,j}$

Table 2. Summary of events, P_G: observed gross precipitation; TF: median throughfall of n collectors; SF: computed stemflow; I: interception loss; n: number of collectors.

Event	Date	P_G (mm)	TF (mm)	TF in % of P_G	SF (mm)	I (mm)	n
1	26/08/2004	12.44	7.07	56.83	0.97	4.4	10
2	26/08/2004	1.77	2.12	119.77	0.14	–0.49	10
3	28/08/2004	19.81	21.23	107.17	1.55	–2.97	9
4	29/08/2004	4.82	3.44	71.37	0.38	1	10
5	30/08/2004	1.01	0.07	6.93	0.08	0.86	10
6	01/09/2004	6.09	3.67	60.26	0.48	1.94	10
7	16/09/2004	21.33	14.91	69.9	1.66	4.76	19
8	25/09/2004	27.17	22.76	83.77	2.12	2.29	19
9	28/09/2004	2.28	0.22	9.65	0.18	1.88	20
10	29/09/2004	7.87	2.46	31.26	0.61	4.8	20
11	04/10/2004	2.03	1.41	69.46	0.16	0.46	19
12	07/10/2004	25.65	18.97	73.96	2	4.68	20
13	12/10/2004	31.24	27.28	87.32	2.44	1.52	20
14	14/10/2004	3.81	0.94	24.67	0.3	2.57	20
15	15/10/2004	3.81	1.56	40.94	0.3	1.95	20
16	19/10/2004	0.76	0.24	31.58	0.06	0.46	20
17	21/10/2004	33.27	24.48	73.58	2.6	6.19	20
18	24/10/2004	10.41	8.89	85.4	0.81	0.71	20
19	27/10/2004	4.31	2.72	63.11	0.34	1.25	20
20	30/10/2004	19.81	17.3	87.33	1.55	0.96	20
21	31/10/2004	3.04	2.42	79.61	0.24	0.38	20
22	02/11/2004	3.81	2.49	65.35	0.3	1.02	20
23	03/11/2004	0.5	0.08	16	0.04	0.38	20
24	04/11/2004	45.46	43.45	95.58	3.55	–1.54	20
25	10/11/2004	30.98	36.07	116.43	2.42	–7.51	20
26	11/11/2004	6.35	4.59	72.28	0.5	1.26	20
27	14/11/2004	63.75	70.46	110.53	4.97	–11.68	19

Table 2. Continued.

Event	Date	P_G (mm)	TF (mm)	TF in % of P_G	SF (mm)	I (mm)	n
28	17/11/2004	23.62	29.81	126.21	1.84	–8.03	20
29	18/11/2004	7.87	7.38	93.77	0.61	–0.12	20
30	20/11/2004	30.98	39.61	127.86	2.42	–11.05	20
31	20/11/2004	0.5	0.23	46	0.04	0.23	20
32	22/11/2004	10.41	7.41	71.18	0.81	2.19	20
33	24/11/2004	5.32	4.25	79.89	0.41	0.66	20
34	25/11/2004	0.5	0.32	64	0.04	0.14	20
35	26/11/2004	0.5	0.55	110	0.04	–0.09	20
36	28/11/2004	5.84	4.33	74.14	0.46	1.05	20
37	30/11/2004	1.52	0.61	40.13	0.12	0.79	20
38	11/01/2005	35.3	35.82	101.47	2.75	–3.27	20
39	14/01/2005	17.52	15.9	90.75	1.37	0.25	19
40	14/01/2005	6.85	6.89	100.58	0.53	–0.57	20
41	16/01/2005	0.5	0.19	38	0.04	0.27	20
42	18/01/2005	1.01	0.69	68.32	0.08	0.24	20
43	22/01/2005	78.23	75.02	95.9	6.1	–2.89	20
44	24/01/2005	23.11	18.83	81.48	1.8	2.48	20
45	25/01/2005	0.76	0	0	0.06	0.7	20
46	26/01/2005	1.01	0.29	28.71	0.08	0.64	20
47	27/01/2005	24.88	24.75	99.48	1.94	–1.81	19
48	28/01/2005	6.09	6.37	104.6	0.48	–0.76	20
49	29/01/2005	11.43	10.07	88.1	0.89	0.47	20
50	30/01/2005	4.57	4.58	100.22	0.36	–0.37	20
51	30/01/2005	1.01	0.51	50.5	0.08	0.42	20
52	31/01/2005	29.46	20.14	68.36	2.3	7.02	20
53	31/01/2005	42.91	40.92	95.36	3.35	–1.36	20
54	04/02/2005	15.24	4.75	31.17	1.19	9.3	20
55	05/02/2005	8.89	5.44	61.19	0.69	2.76	20
56	06/02/2005	1.27	0.52	40.94	0.1	0.65	20

Table 2. Continued.

Event	Date	P_G (mm)	TF (mm)	TF in % of P_G	SF (mm)	I (mm)	n
57	08/02/2005	43.43	38.62	88.92	3.39	1.42	20
58	09/02/2005	14.73	13.77	93.48	1.15	–0.19	20
59	11/02/2005	37.84	24.34	64.32	2.95	10.55	20
60	13/02/2005	2.54	1.93	75.98	0.2	0.41	20
61	15/02/2005	2.03	1.54	75.86	0.16	0.33	20
62	17/02/2005	30.22	27.24	90.14	2.36	0.62	20
63	17/02/2005	4.57	3.66	80.09	0.36	0.55	20
64	18/02/2005	2.28	1.31	57.46	0.18	0.79	20
65	19/02/2005	30.48	24.07	78.97	2.38	4.03	20
66	21/02/2005	1.02	0.66	64.71	0.08	0.28	20
67	21/02/2005	23.36	24.03	102.87	1.82	–2.49	20
68	23/02/2005	33.27	50.5	151.79	2.6	–19.83	19
69	24/02/2005	3.04	0.57	18.75	0.24	2.23	20
70	26/02/2005	1.52	0.82	53.95	0.12	0.58	20
71	27/02/2005	31.75	24.39	76.82	2.48	4.88	20
72	28/02/2005	17.27	18.52	107.24	1.35	–2.6	20
73	01/03/2005	8.12	5.74	70.69	0.63	1.75	20
74	02/03/2005	11.68	13.86	118.66	0.91	–3.09	20
75	04/03/2005	6.09	4.02	66.01	0.48	1.59	20
76	05/03/2005	57.66	61.56	106.76	4.5	–8.4	20
77	07/03/2005	6.09	1.67	27.42	0.48	3.94	20
78	07/03/2005	3.04	1.65	54.28	0.24	1.15	20
79	10/03/2005	6.09	4.43	72.74	0.48	1.18	19
80	11/03/2005	2.79	1.72	61.65	0.22	0.85	20
81	13/03/2005	1.77	1.61	90.96	0.14	0.02	20
82	14/03/2005	21.84	20.37	93.27	1.7	–0.23	20
83	16/03/2005	16.75	14.41	86.03	1.31	1.03	20
84	17/03/2005	10.66	12.65	118.67	0.83	–2.82	20

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Table 2. Continued.

Event	Date	P_G (mm)	TF (mm)	TF in % of P_G	SF (mm)	I (mm)	n
85	18/03/2005	8.38	6.82	81.38	0.65	0.91	20
86	20/03/2005	2.03	2.71	133.5	0.16	–0.84	20
87	20/03/2005	4.57	3.57	78.12	0.36	0.64	20
88	21/03/2005	1.01	0.72	71.29	0.08	0.21	20
89	23/03/2005	3.04	0.61	20.07	0.24	2.19	20
90	28/03/2005	33.52	30.21	90.13	2.61	0.7	20
91	01/04/2005	1.77	1.22	68.93	0.14	0.41	20
92	02/04/2005	14.47	12.06	83.34	1.13	1.28	20
93	03/04/2005	4.82	3.48	72.2	0.38	0.96	20
94	04/04/2005	2.54	1.31	51.57	0.2	1.03	20
95	05/04/2005	4.57	2.53	55.36	0.36	1.68	19
96	06/04/2005	0.76	0.25	32.89	0.06	0.45	20
97	10/04/2005	4.57	2.73	59.74	0.36	1.48	20
	Total:	**1308.66**	**1175.36**		**102.2**	**31.1**	

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Table 3. Canopy parameters used for interception modeling.

Parameter	Value
S_C (canopy capacity) (mm)	0.72±0.44
c (canopy cover)	0.97
P'_G (P_G needed to saturate the canopy) (mm)	0.74
$\overline{E}_C$ (mean evaporation rate) (mm h^{-1})	0.21
$\overline{R}$ (mean rainfall rate) (mm h^{-1})	6.66
p_t (rainfall diverted to trunk)	0.08
S_t (trunk storage capacity) (mm)	0.22

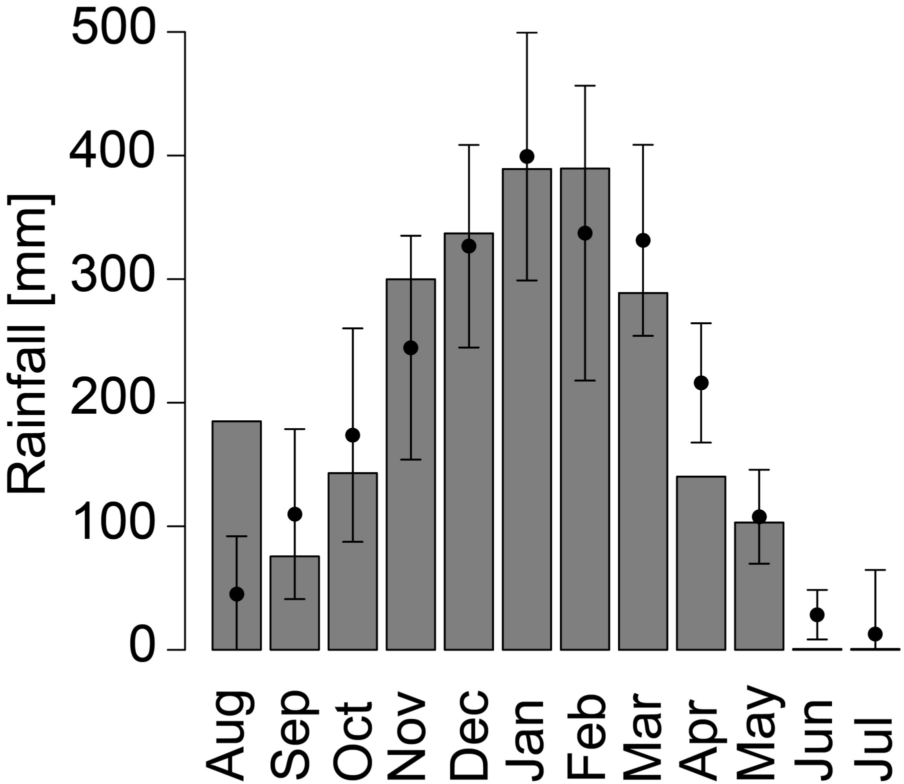

Fig. 1. Monthly rainfall data from August 2004 to July 2005. The solid circles and the vertical lines are the mean and standard error, respectively for the period 1984–2003.

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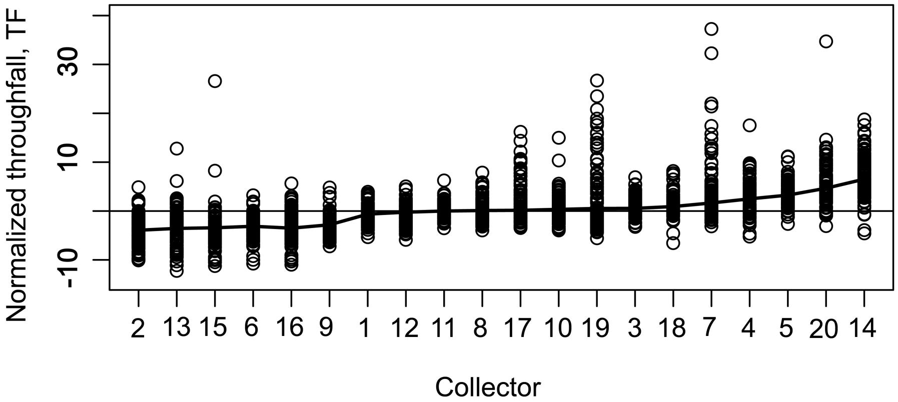

Fig. 2. Plot of normalized throughfall, $\tilde{T}F$, for the whole period. Each circle represents the event throughfall volume at a single collector, normalized to zero mean and unit variance for that event. The collectors are plotted on the horizontal axis and ranked by their means, $\tilde{T}F$, which are connected by the black curve.

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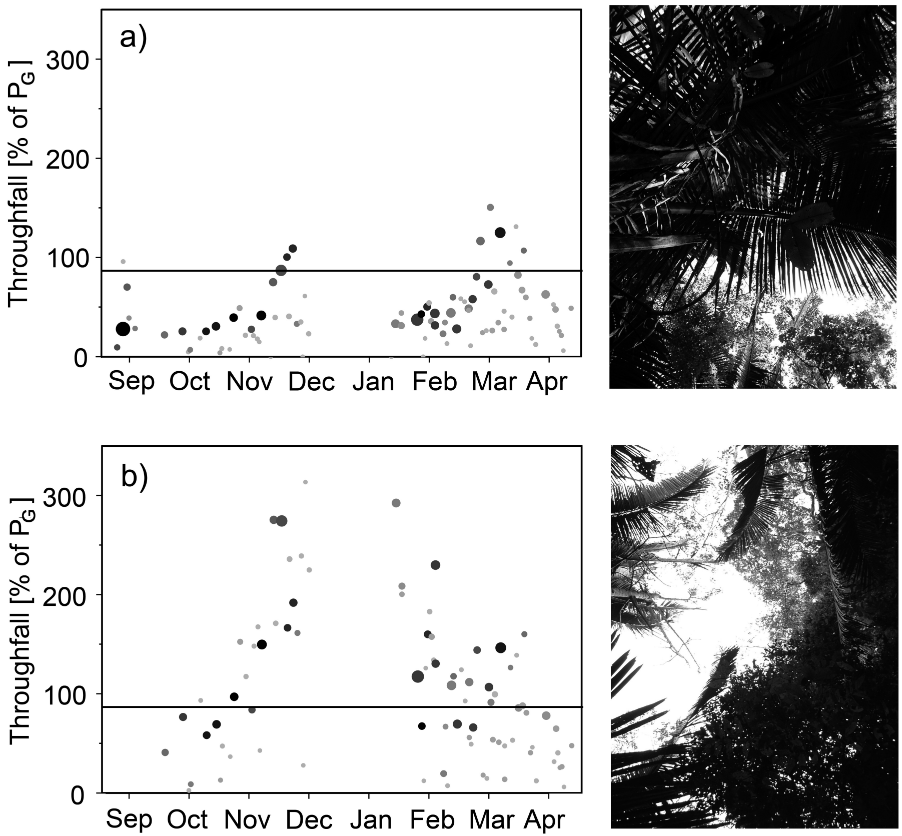

Fig. 3. Temporal patterns of throughfall percentages of incident rainfall for two collectors standing only 5 m apart from each other. Each event is represented by a dot whose diameter is proportional to rainfall amount. Varying colours from light grey to black illustrate low and high rainfall intensity (I_{10} max) values, respectively. The photographs on the right site show the vegetation above these two collectors.

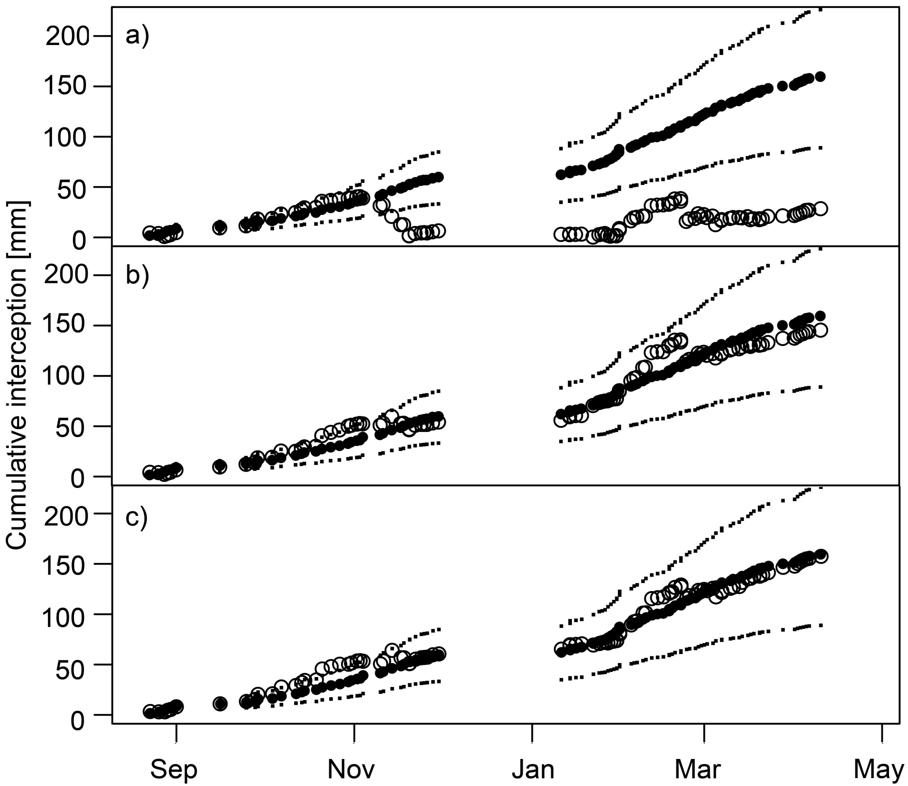

Fig. 4. Cumulative totals of calculated (open circles) and expected (solid circles) interception loss for **(a)** all collectors (n=20), **(b)** collectors not showing temporal patterns of throughfall percentages (n=9) and for **(c)** collectors without obvious influence of the palm species *Orbignya phalerata* (n=6). The dots indicate the uncertainty of the modeled interception resulting from the uncertainty in S_C.

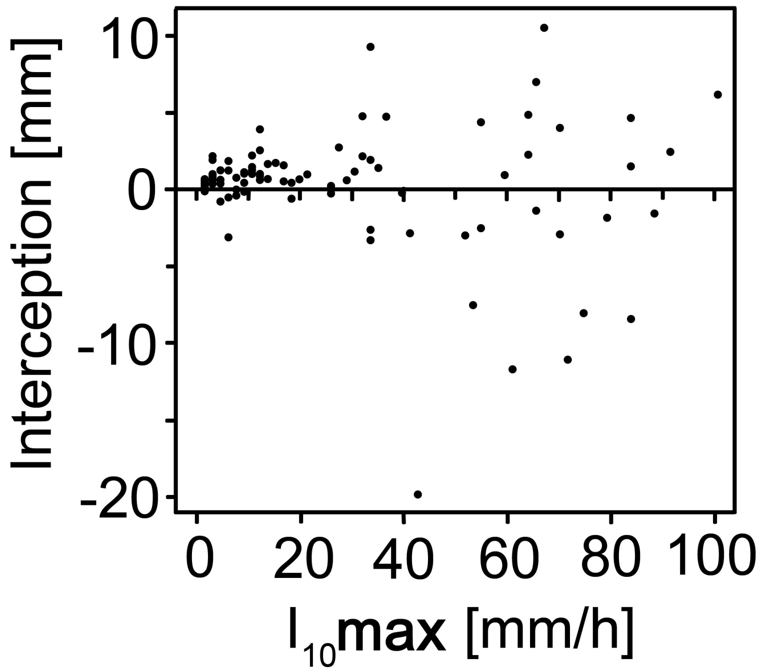

Fig. 5. The relationship between calculated interception loss and maximum 10-min rainfall intensity.

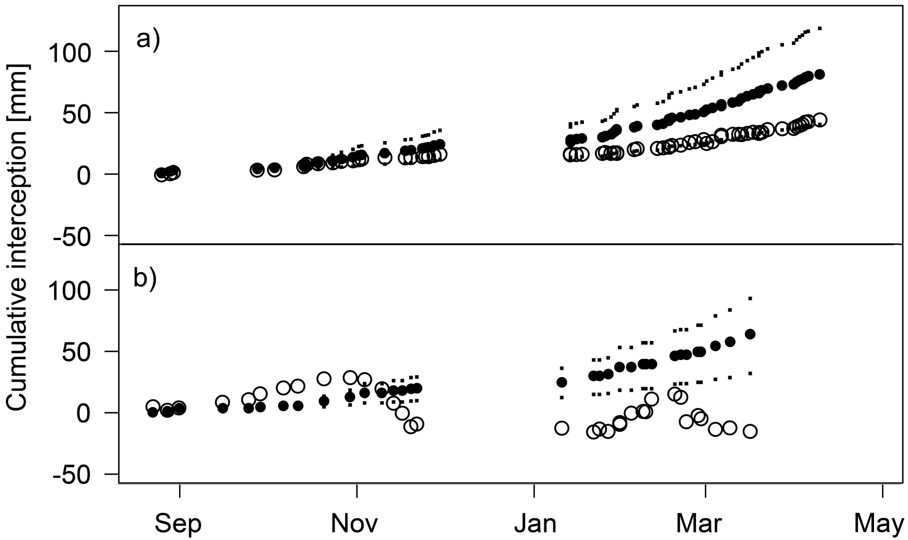

Fig. 6. Cumulative totals of calculated (open circles) and expected (solid circles) interception loss for maximum 10-min rainfall intensities **(a)** I_{10} max≤30 mm h^{-1} and **(b)** I_{10} max>30 mm h^{-1} including all collectors (n=20). The dots indicate the uncertainty of the modeled interception resulting from the uncertainty in S_C.